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Energy and cost assessment of 3D printed mobile case covers

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Abstract

Sustainable manufacturing emphasizes efficient production, whilst upholding economic, environmental, and societal commitments. One major challenge for sustainability arises in short lifecycle products such as mobile phone covers. The market demands quick product launch and responsive fulfilment, which is typically achieved through make-to-stock production using injection moulding. This approach necessitates production is based on demand forecasts, which frequently leads to overproduction and much unsold waste product. 3D printing technologies enable a make-to-order production model, allowing customers to self-manufacture mass customized products as needed. Moreover, in the framework of circular economy, 3D printing empowers the final user with full control of the end-of-life product disposal management. These capabilities suggest 3D printing may afford improved sustainability, but to-date there has been little empirical validation of this proposition. This paper addresses this gap through a comparison of 3D printed and injection moulded production, providing a detailed quantitative evaluation of energy and costs for both manufacturing approaches.

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Keywords: 3D Printing; Sustainability; Make-to-Order; Make-to-Stock; Energy; Cost.

1. Introduction

The technologies of 3D printing (sometimes termed Additive Manufacturing) are today well-established as valuable tools for prototyping, tooling, and the direct manufacturing of end-use parts. Whilst is widely acknowledged that many 3D printing technologies are still beset with technical challenges that affect performance and quality capabilities, efforts by commercial manufacturers and academic researchers are gradually overcoming these limitations. As a result, 3D printing is being employed in an ever-increasing range of applications, and this positive trajectory is expected to continue for an industry that is enjoying very strong growth [1].

Currently the manufacturing achieved using 3D printing represents a tiny proportion of the totality of world manufacturing output, but for some industries it has become the dominant approach to production [2]. As 3D printing becomes more prevalent in real world factories, so too does the need to consider sustainability in terms of economic, social, and environmental factors, and it is this sustainability agenda to which the current study makes its contribution in the context of 3D printed mobile case covers. In this paper we explore how 3D printing may allow a fundamental shift in the mode of production for the case cover product, moving from a Make-To-Stock (MTS) approach employing Injection Moulding, to a Make-To-Order (MTO) approach utilizing 3D printing. Through this investigation we show the opportunities for 3D printing to contribute to the sustainability agenda, and identify pertinent areas for future research.

2. Literature Review

2.1. Assessing sustainability in 3D printing

Research on sustainability for 3D printing has increased significantly in recent years, reflecting the growing importance

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of the topic as the industry matures. Whilst sustainability in operations and supply chain research is typically considered in terms of economic, social, and environmental considerations [3], for 3D printing the majority of studies focus on energy consumption, either in terms of different 3D printing technologies or 3D printing vis-à-vis conventional manufacturing technologies [4,5]. Typically such comparisons are performed in terms of financial performance (i.e. monetary costs), environmental performance (e.g. CO2 / pollution outputs), or both. There is, however, limited literature that explores energy consumption in significant detail. One particularly useful resource is that of Le Bourhis [6], who in recognizing that different 3D printing processes have different energy consumption profiles, provide a synthesis of current research for a variety of machines and materials. However, for each machine/material combination the paper is reliant on only one source, and it is noted by Ford and Despeisse [4] that there is much inconsistency in the findings of these types of studies. Better investigations clearly note such issues in their work. For example, in explaining the difference between their results and those of prior studies, Baumers et al [7] identify that capacity utilization is likely to affect energy utilization, and factors such as these need to be carefully considered in energy assessment works. In reviewing the state of research, such observations lead Huang et al. [8] to assert that there is a need for a clearly defined methodology that can standardize assessments between studies, though this has not yet been achieved.

2.2. Leveraging the benefits of Make-To-Order (MTO) production

One of the longest established advantages of 3D printing is that it offers the ability to cost-effectively produce parts at very low volumes; in theory making batch sizes of one economically viable [9]. In addition, 3D printing offers the ability to achieve quick response manufacturing of individually customized products [10]. Combined, these capabilities support a progression in 3D printing towards a MTO model of production, whereby product designs are created, and materials sourced in anticipation of a customer order [11]. Such an approach is in stark contrast to the ‘traditional’ MTS mode of production, where finished goods are completed before the customer order is placed with the manufacturer.

The juxtaposition between MTO and MTS is clear and well established: in order to satisfy customers MTO necessitates much more responsive production than MTS, but because the details of the order are known at the time of manufacture, for MTO the likelihood the product will meet the customer requirements is high, and risks of product obsolescence are low.

In an MTS system accurate forecasting of demand is essential, since overproduction will lead to excess stock holding, and underproduction will lead to stock-outs. The former of these is already well-established as having negative connotations for environmental sustainability [4], with excess production needing to be disposed of appropriately. Far less attention has been extended to the sustainability implications of underproduction, however given the scarcity of resources is a fundamental driver of sustainability [12], it is reasonable to extend the discussion in terms of manufactured resources. For some manufactured products (e.g. medical devices), shortages have a very negative impact on the societal pillar of sustainability. As a result, through MTO the potential to produce exactly what is required when it is required offers the potential for major sustainability benefits.

3. Research Method

The authors have previously explored the material flow in traditional MTS production using Injection Moulding, and proposed 3D printing as an alternative process suitable for MTO production with a much shorter supply chain [13]. The current study builds on these foundations to examine the sustainability of mobile case cover manufacture using both MTO and MTS production.

In the current preliminary analysis, the two models are compared considering direct materials cost and energy consumption only. Operator cost, and various indirect costs such as depreciation and overhead recovery are not considered, since the focus of this study is on environmental impact, rather that attempting to provide exact estimate of the manufacturing costs and related profits. The functional unit for the assessment is one Apple iPhone 5 cover and demand statistics for iPhone 5 model adoptions in the USA have been sourced from the web [14]. The STL model of the focal case cover is available for download in the open Thingiverse library [15].

With the aim of performing a thorough and correct comparison, the same polymeric material for the case cover is considered in both Injection Moulding and 3D printing processes. In particular, case covers are fabricated from ABS (Acrylonitrile-Butadiene Styrene), which is one of the most common materials used for 3D printing filaments.

Starting from the material flow, the performed analysis considers a Cradle-To-Gate approach as described hereafter for each production model and process. The system boundaries for the two compared processes are shown in Fig. 1. Most of material data is extracted from the database of the CES Edupack 2016 software [16] by Granta Design Limited.

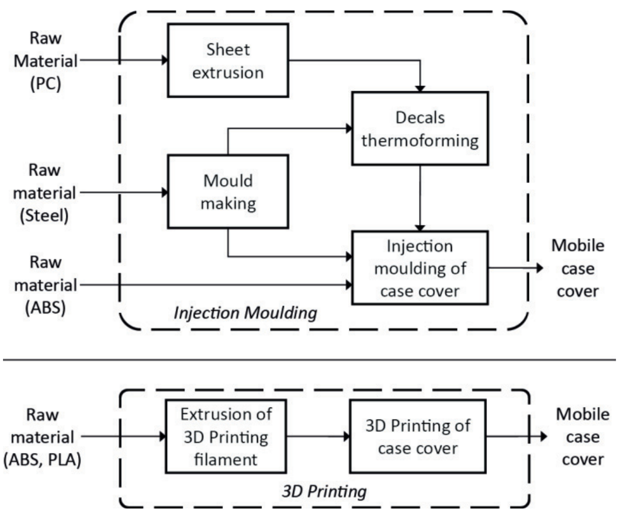

Fig. 1 – System boundaries for energy and cost assessment.

4. Results

4.1. Make-To-Stock (MTS) manufacturing using Injection Moulding

The Injection Moulding process requires the use of a tool (hereafter termed 'the mould') whose cavity is the inverse shape of the product, but is slightly oversized to take into account the material shrinkage that occurs during processing. Although different materials are used for the mould plates, for the sake of simplicity, in the analysis we assume that all the plates are made of P20 steel, whose alternative coding is 2311. The iPhone 5 cover has overall dimensions of 127.8 mm x 62.9 mm x 10.8 mm. Including additional space for the feeding system, the standard elements of the mould (guide pins, etc.) and action inserts required for undercut withdrawal, we assume that the mould plates have a standard size of 346 mm x 446 mm. The thickness of the plates varies with their function (Table 1), and mould is composed of the top clamp plate, the cavity plate, the core plate, the two space plates, the two ejector plates, and the bottom clamp plate.

Table 1. Plates of the injection mould

Element	Dimensions (in mm)		
	Width	Length	Thickness
Top Clamp plate	396	446	36
Cavity plate	346	446	76
Core plate	346	446	96
Space plate (right)	62	446	96
Space plate (left)	62	446	96
Ejector top plate	218	446	17
Ejector bottom plate	218	446	22
Bottom clamp plate	396	446	36

Disregarding the material of small standard elements such as guide pins, screws and ejectors, the plates account for a volume of 0.048 cubic meters. Considering a density of 7850 kg/m3 for the P20 steel, the mould weights about 380 kg. As concerns sustainability, an additional 10% of material is assumed as an allowance for machining operations after casting. The embodied energy in primary P20 steel production is 25.65 MJ/kg [16], whereas the energy required for casting is 11.50 MJ/kg [16]. Machining operations require a different amount of energy, depending on the type of operation and removed material allowance. 1.78 MJ/kg are used in coarse machining of P20 steel [16]. Subsequent fine machining consumes 13.35 MJ/kg and finally grinding machining requires 26.20 MJ/kg [16]. We assume that 8.0% of the machining allowance is removed by coarse machining, while the fine machining operation removes 1.5% of the material and the remaining 0.5% is ground. The detail of the energy demanded for the fabrication of the mould is provided in table 2.

To understand the potential cost of the mould, we interviewed experts from the injection moulding industry. They reported that a good quality tool intended for longevity and quality part production would cost up to 10,000 € and would achieve five years of utilization (at 85%) with a 20 second cycletime for the mobile case cover production. Therefore, assuming three 8-hour shifts per day along 365 days with 85% utilization, the expected mould productivity is 1.34 million case covers per year.

Table 2. Energy consumption for mould fabrication

Manufacturing step	Specific energy (MJ/kg)	P20 steel weight (kg)	Energy (MJ)
Primary production	25.65	417.6	10711.5
Casting	11.50	417.6	4802.4
Coarse machining	1.78	33.4	59.6
Fine machining	13.35	6.3	83.6
Grinding operation	26.20	2.0	54.7
		Total energy	15711.8

The raw material for injection moulding is pellets of ABS, and costs of approximately 2.70 €/kg. To produce this material requires approximately 95.25 MJ/kg of embodied energy [16]. The average energy for injection moulding of ABS material is approximately 18.55 MJ/kg [16]. Therefore, considering an additional 10% of material for the feeding system, a single cover requires 18.7 grams of ABS material. This leads to an energy expense of 1.784 MJ for the ABS production and 0.347 MJ for the material transformation by injection moulding. The energy required for the fabrication of the mould accounts for 15711.8 MJ; when considered over 6,700,000 case covers this results in an energy requirement of 0.002 MJ.

The average European cost of the electricity is considered as an estimate of the cost related to material transformation (disregarding equipment, labour, and overheads). The average European cost of electricity is 0.114 €/kWh [17]. The cost of 17 grams of ABS pellets for the cover is 0.05 €, and the injection moulding cost is about 0.26 € per part. This was determined using [18] for 18.7 grams (cover weight + 10% of the weight for the feeding system), 20 second cycle time, the average European electricity cost and 7446 production hours per year. The mould cost could almost be disregarded, because of the large production volumes considered. In fact, it accounts for 10,000 € over 6.7 million parts, that makes less than 1 cent per part.

Whilst this data provides an overview of simple mobile case manufacture, there are several processes that can be used for finishing the injection moulded case cover with different designs to meet the customer tastes and desires. One of the most widely used process is a process of in-mould decoration. This requires the printing of a decorative pattern on a label of thin sheet polycarbonate (PC) material. The label is first shaped by thermoforming to adapt it to the form of the back and side surfaces of the cover, and is then trimmed out of the PC sheet. The label is then inserted into the mould prior to injecting the molten mass of material of the cover. At the end of the injection moulding step, the case cover will be extracted from the mould with the decoration included in its back face.

To account for the finishing of the cover, the PC material production has an embodied energy of 108.5 MJ/kg [16], while the material extrusion process that is used for transforming the pellets into sheet requires 6.085 MJ/kg. 100 sheets of PC material with dimensions of 622 mm x 1230 mm x 0.254 mm are sold at about 350 €. We assume that each sheet can be trimmed and divided into 12 equal parts, enabling the forming and printing of 36 decals in total. For productivity reasons, the thermoforming mould can shape three labels over a portion of the PC sheet whose approximate dimensions are 310 mm x 200 mm.

The mould for the thermoforming operation will be formed by a top clamp plate, the cavity plate, the core plate, and the bottom clamp plate. Considering a plate size of 346 mm x 396 mm, it can be estimated that the mould costs about 7,500 €. With the same assumptions of the injection mould regarding the energy consumption, the production of the thermoforming mould requires 7302.80 MJ.

The PC material has a density of 1200 kg/m3 [16] and the embodied energy for its primary production is 108.5 MJ/kg, and for extrusion is 6.085 MJ/kg. The thermoforming operation takes about 10 seconds and it is carried out using a machine with a power of 20 kW. Therefore, the fabrication of the PC sheet for decals requires 0.70 MJ per decal for material production, 0.04 MJ per decal for sheet extrusion, 0.07 MJ per decal for thermoforming. The cost of each decal is about 0.10 € per part.

Based on these values it is calculated that the cost of a single injection moulded cover (without decals) is about 0.31€ and it raises to 0.41 € if decals are added.

4.2. Make-To-Order (MTO) manufacturing by 3D printing

In this study we utilize a widely available and relatively inexpensive desktop 3D printer: the Makerbot Replicator 5th Generation.

The layer-by-layer 3D printing of the iPhone 5 case cover (Fig. 1) necessitates support structures are employed for overhanging features of the design. These are found in the internal area of the design, close to the border and the square slot for the mobile sleep key. Whilst the case cover is produced from ABS material, supports are instead fabricated from Polylactic Acid (PLA). This is standard practice for these technologies, and once printing of the cover is complete, the supports are easily dissolved by immersion in a sodium hydroxide solution.

The Makerbot Desktop software was used to compute the 3D printing path using a layer thickness of 0.10 mm. The amount of material required for the raft at the base of the cover and the support structures for the overhangs is approximately 16.5 grams, almost as much as the ABS material of the cover.

The printing operation takes approximately 4 hours. The cost of both the ABS and PLA filaments is about 25 €/kg for a good quality filament, assuming that a high number of covers will be fabricated and therefore that purchased quantity of filament is consistent with industrial levels of production.

The average energy consumption for a Makerbot machine is about 0.11 kW for the ABS material and 0.08 kW for the PLA material [19]. This is because of the higher temperature (230÷260°C) required to melt and extrude the ABS filament compared to the PLA (175÷220 °C) [20].

The energy embodied in the primary production of the PLA material is about 51.70 MJ/kg [16] and the extrusion of the material requires 5.94 MJ/kg [16], while 6.08 MJ/kg [16] are used for extruding the ABS filament.

Therefore, for each cover, the production of ABS pellets accounts for 1.619 MJ, the extrusion of ABS to filament requires 0.103 MJ, and the 3D printing of the cover uses 0.223 MJ. In terms of the PLA support material, the production of the pellets requires 0.853 MJ, the extrusion of the PLA filament uses 0.098 MJ, and the 3D printing of the support structures accounts for 0.158 MJ.

The cost of the ABS material used for the cover fabrication is about 0.43 €, while the PLA for supports is 0.41€. The energy consumption during 3D printing costs 0.05 € per case cover. Thus the total cost of the 3D printed ABS case cover for the iPhone 5 is approximately 0.88 € without accounting for 3D printer depreciation, labour costs and overheads.

A comparison of the energy required to produce a single case cover using Injection Moulding and 3D printing is provided in Fig 2, visually demonstrating the additional energy needed when employing 3D printing. The breakdown percentages are shown between parenthesis. It is noted that for Injection Moulding with in-molded decals, raw ABS material production accounts for 60.4% of the total energy used, while 11.8% of energy is employed in the moulding operation.

The production of the PC decals requires about one quarter of the total energy and most of its demand is originated by the production of raw PC material (23.8%). Within the overall production context, the energy used in the manufacture of the moulds is almost negligible.

A comparison of the cost of a single cover using Injection Moulding and 3D printing is provided in Fig 3, with breakdown percentages between parenthesis. The higher cost of the 3D printed cover has to be attributed to the expensive 3D printing filament, that costs about 10 times more than the raw material. As concerns Injection Moulding, the cost associated with the mould making becomes negligible when divided by high production volumes.

5. Conclusions

This study has identified some interesting opportunities for 3D Printing using MTO, some of which can be exploited today, and other that may have greater significance in the future. From the economic perspective, it has been shown that like-for-like production between 3D printing and Injection Moulding still favours the conventional approach. Simple cases (which would not require in-mould decoration for Injection Moulding) cost three times as much to produce using 3D printing; more complex cases are closer to twice the price through 3D printing. This is a significant finding; normally mobile phone cases are produced in very high volumes, and so this increased manufacturing cost would be difficult to justify in a like-for-like process swap.

However, such calculations on cost assume that the entirety of the injection-moulded capability for case production will be utilized, and this is unlikely to be fully realized. Currently the cost of the tool is amortized over the whole production run, and this makes the tool cost negligible. Should expected demand be less than the tool's capability the manufacturer must either 1) product less parts, but at increased costs to ensure full recovery

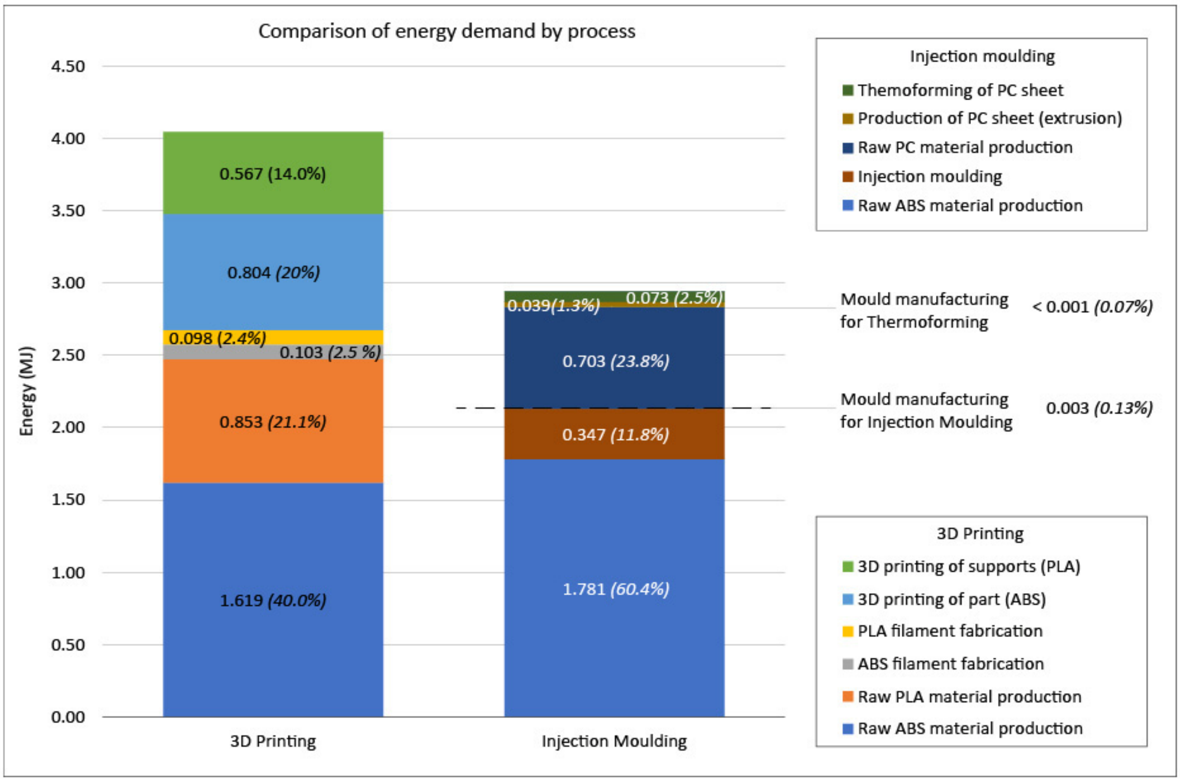

Fig. 2 – Comparison of energy demand by process in the production of an iPhone 5 case cover

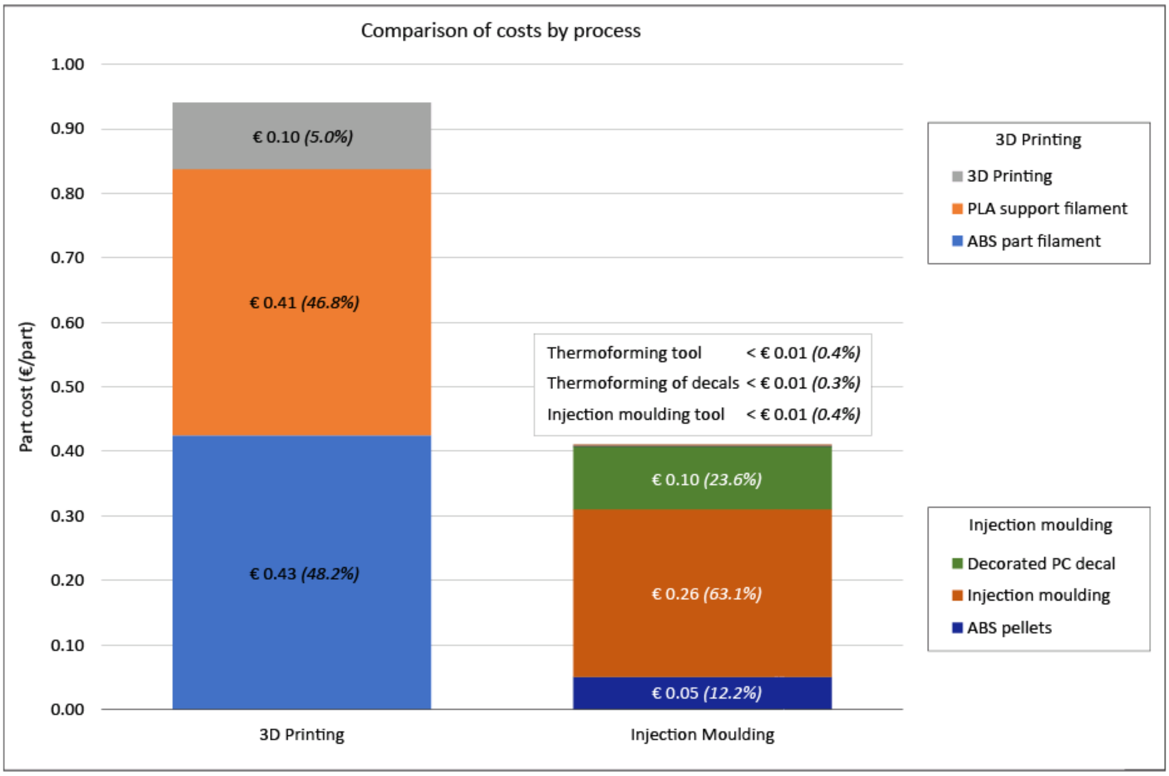

Fig. 3 – Comparison of costs by process in the production of an iPhone 5 case cover

of the tool cost; or 2) produce to the capability of the tool, but acknowledge that over-production may occur, leading to stockpiles of potential waste. Given that mobile case lifecycles tend to be short [13], this latter option may be particularly risky.

In terms of energy usage, 3D printing also performs relatively poorly in the like-for-like comparison with Injection Moulding. Cases produced using 3D printing require approximately twice as much energy than their conventionally produced counterparts, which again for high-volume production constitutes a negative contribution to sustainability objectives. However, as with the financial considerations, this assumes that all parts produced serve a purpose; for Injection Moulding over-production leads to waste, for which additional energy will be needed to transport and recycle the plastic for future utilization.

Both the financial and energy consumption findings underline the observation that 3D printing would make a poor like-for-like MTS swap. The advantage of 3D printing is, however, that it can readily promote MTO to produce exactly what the customer requires, reducing the reported uncertainties in demand. By doing so, some of the financial and environmental costs associated with both underproduction and overproduction can be mitigated, making the processes much more attractive to potential manufacturers.

This initial study has therefore shown like-for-like comparisons of the production technologies, and highlighted their relative merits and demerits. Further work is now needed to build on these findings in the derivation of practical production scenarios to explore various demand profiles and manufacturing responses. This will allow a better understanding of the circumstances in which Injection Moulding is truly advantageous, which circumstances 3D printing is a beneficial approach, and whether there are any opportunities for a combination of both technologies to be optimal. In turn, such research may also be extended to full-lifecycle assessments for 3D printing, extending the limited existing research in this area (e.g. [21-23]).

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